Results from Oxygen Enhanced Fire Tests in LD-3 Cargo Containers and Oven Tests on Cylinder Overpacks

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ABSTRACT

The release of 11 and 22 cubic feet of oxygen during cargo fires inside an LD-3 container inerted with halon demonstrated the extreme hazards associated with an oxygen-enriched fire. The tests were conducted in support of pending rulemaking to prohibit the transportation of oxidizers, including pressurized cylinders, in the cargo compartments of passenger-carrying airplanes. Under consideration is whether the transport of oxygen cylinders should be permissible in cargo compartments protected with fire detection and suppression systems. A 22-cubic-foot oxygen-enriched fire burned through the ceiling of the container and destroyed it. Subsequent tests focused on the insulative properties of overpacks, shipping containers for the oxygen bottles, with regard to preventing pressure-relief of the stored oxygen during a halon-suppressed cargo fire. The testing was undertaken several months ago at the request of Flight Standards, following a Public Hearing in which industry, pilot, medical oxygen and oxygen-user representatives pressed the Federal Aviation Administration (FAA) and Research and Special Programs Administration (RSPA) to allow for the cargo transport of oxygen bottles.

BACKGROUND

A fatal in-flight fire occurred onboard a ValuJet DC-9 on May 11, 1996. During this accident, an extremely intense fire fueled by solid oxygen generators erupted in the class D compartment, burned out of control into the passenger cabin, and eventually caused the aircraft to crash, resulting in 110 fatalities. In the wake of this accident, Research and Special Programs Administration (RSPA) published an interim final rule that temporarily prohibited the transportation of chemical oxygen generators as cargo in passenger-carrying operations. The RSPA interim final rule was adopted on December 30, 1996, resulting in the permanent ban on carriage of chemical oxygen generators as cargo on all passenger-carrying flights. On the same date, RSPA proposed to limit the carriage of oxidizers, including compressed oxygen, to accessible locations on cargo aircraft, and prohibit such oxidizers from being transported in all passenger-carrying aircraft. Industry, pilot, and user groups have requested an exemption to allow for the shipment of compressed oxygen in class C cargo compartments, which have fire detection and suppression systems. In the event of a fire in a class C compartment, the fire would be detected and agent discharged to suppress the fire. In the event that the fire is not fully extinguished, which would be the case if the origin were a deep-seated fire, the temperatures in the compartment could reach 400^{o}F. The major concern with the shipment of oxygen cylinders under this scenario is that the elevated temperatures would cause the cylinder pressure to increase, resulting in the pressure relief mechanism opening. If this occurs, the contents of oxygen could vent directly into the fire, causing a potentially catastrophic event.

There are different types of pressure relief devices and cylinders used for storing breathing oxygen. There are two types of rupturing relief valves, a frangible disc that will fail under excessive pressure (typically 2500 psi), and a thermal disc that will fail when the temperature exceeds 165^{o}F or 225^{o}F, depending on the type. There is also a spring-loaded relief valve that will vent at approximately 2000 psi, so only a percentage of the oxygen would be vented if exposed to elevated temperatures. The rupture disc relief device is the only type used on gaseous oxygen cylinders for crew and passenger breathing systems on commercial transport aircraft, so the research was limited to this type only. Ironically, the rupture disc type pressure relief devices pose a more serious concern in a fire environment, since it is possible for the entire contents of the oxygen cylinder to be discharged at elevated temperatures.

Oven Test Arrangement. The primary focus of the research was to determine the hazards associated with oxygen cylinders involved in an aircraft cargo fire. Since there are inherent dangers associated with the heating of pressurized oxygen cylinders, it was decided that all fire tests would be conducted using a remotely placed oxygen cylinder. Gaseous oxygen could be safely piped into the LD-3 test container to provide the same result as an actual cylinder placed directly in the fire. In order to determine the appropriate time and rate of oxygen release during the fire, a series of tests were first run in an oven to measure the response of several different sized cylinders. For safety purposes, the cylinders were emptied of all gaseous oxygen, then re-pressurized with gaseous nitrogen to 1800 psi.

A large, industrial-type electric conduction oven was used for testing. The oven had internal dimensions of 37.5 by 26 by 25 inches, and could ramp up to 400^{o}F in approximately 6 minutes. During the tests, the cylinders were attached to a steel frame that fit snugly into the test oven to prevent cylinder movement and subsequent damage to the oven. The cylinder surface temperature was continuously monitored during tests using three thermocouples attached directly to the cylinders, and a fourth thermocouple was located mid-height in the oven for comparison. A copper tube line was also run from the cylinder valve head, which connected to a pressure gauge, allowing the internal pressure of the cylinder to be measured continuously during the heating process.

Oven Test Results. During the first oven test, a 3HT-type 76.5 cubic foot cylinder was placed in the test frame holder. The cylinder measured 7.25 inches diameter by 29.75 inches length, excluding valve assembly. After start of the test, the rupture disc activated at 9 minutes 53 seconds, and required 33 seconds for the cylinder to fully evacuate. The temperature of the cylinder was 285^{o}F, and the temperature inside the oven was approximately 380^{o}F at the time of release (figure 1). The cylinder internal pressure was approximately 2650 psi at the time of rupture disc activation.

A second test was run under nearly identical conditions using a larger 115 cubic foot cylinder that measured 9.00 inches by 29.56 inches. During this test, the rupture disc activated at 15 minutes 23 seconds, and required 1 minute 12 seconds to fully empty. The internal pressure was 2600 psi, and the cylinder surface temperature ranged between 300 and 320^{o}F (figure 2).

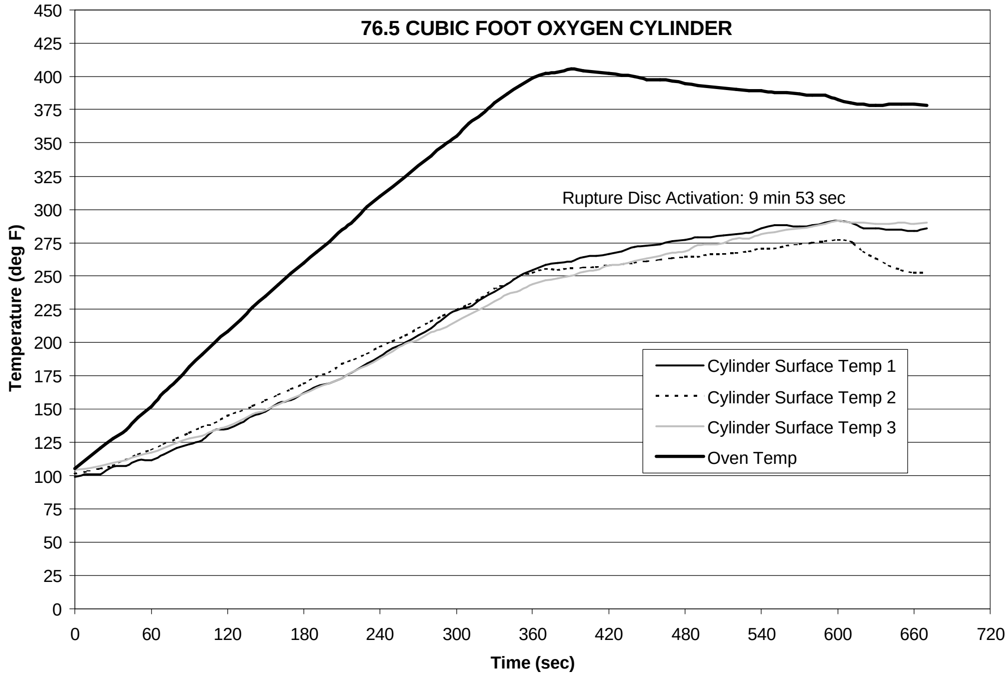

Figure 1. Oven Test Result of 76.5 ft^3 Oxygen Cylinder

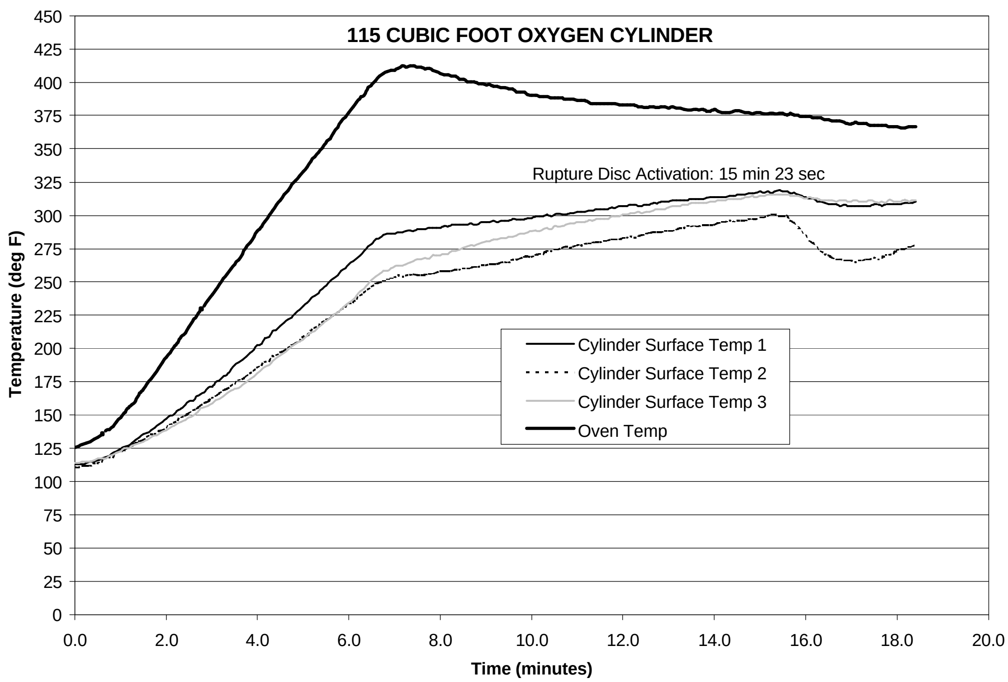

Figure 2. Oven Test Result of 115 ft^3 Oxygen Cylinder

A final test was run using a small, 11 cubic foot "walkaround" bottle that is typically used by flight attendants in the event of cabin depressurization. The cylinder was a type 3AA, and measured 3.25 by 18.75 inches. A malfunction with the oven temperature control resulted in a lengthy heating period, however the rupture disc activated during temperature ramp-up at 17

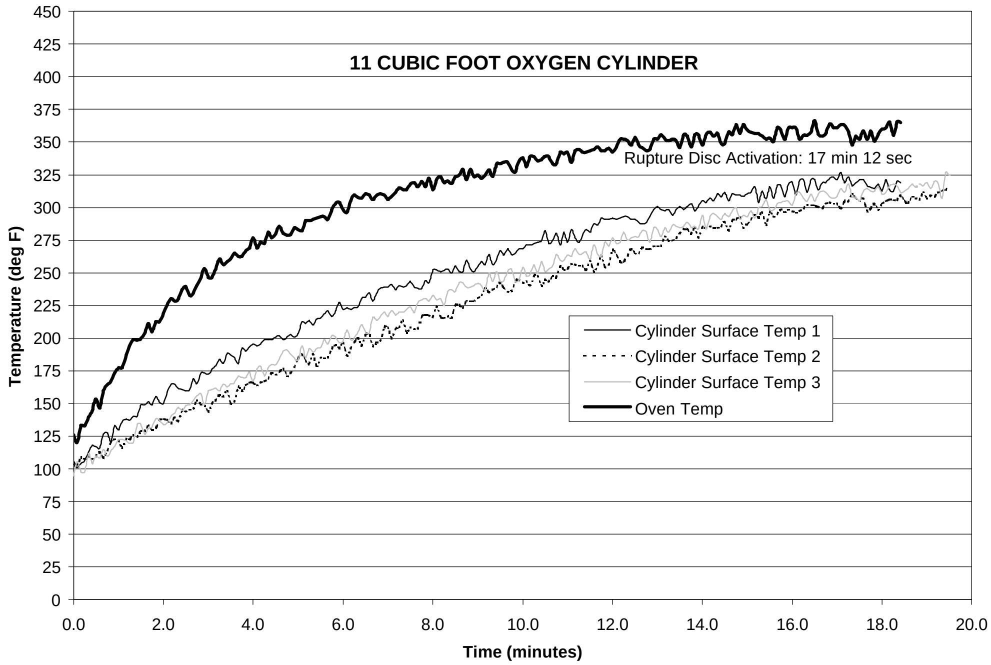

Figure 3. Oven Test Result of 11 ft^3 Oxygen Cylinder

minutes 12 seconds. The oven temperature had reached between 350 and 370^{o}F during release, at which point the cylinder surface temperature was between 300 and 325^{o}F. The cylinder required only 5 seconds to fully discharge, and the pressure was observed to be approximately 2500 psi. (figure 3).

FULL-SCALE FIRE TESTS

LD-3 Test Arrangement. In order to determine the impact of oxygen release during a fire, a steel-framed receptacle was constructed in the shape of an LD-3 container, which is typically used in the lower lobe of wide-bodied aircraft (DC-10, 747, 767, L-1011). The test container has an internal volume of 169 cubic feet, and can be rebuilt in the event of sidewall or ceiling damage. The test container utilized sheet steel on most of the surfaces, except for the top and front side, which was aluminum (0.63-inch thick). The fire load material consisted of shredded-paper-filled cardboard boxes measuring 18 by 18 by 18 inches. The boxes were loaded into the container in two tiers, each containing 9 boxes. An additional 2 boxes were loaded into the container for a total of 20. Thermocouples were placed on the four sides and ceiling of the test container. A gas sampling station was also installed, which contained intake ports at heights of 21 inches, 37 inches, and 54 inches from the floor. These lines passed through a series of filters prior to entering the gas analyzers, which continuously monitored for carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and halon 1301. A large 1000-lb. halon 1301 tank was used for fire suppression. A 0.375-inch diameter transfer line was attached from the tank to a discharge port mounted in the center of the test container ceiling (figure 4).

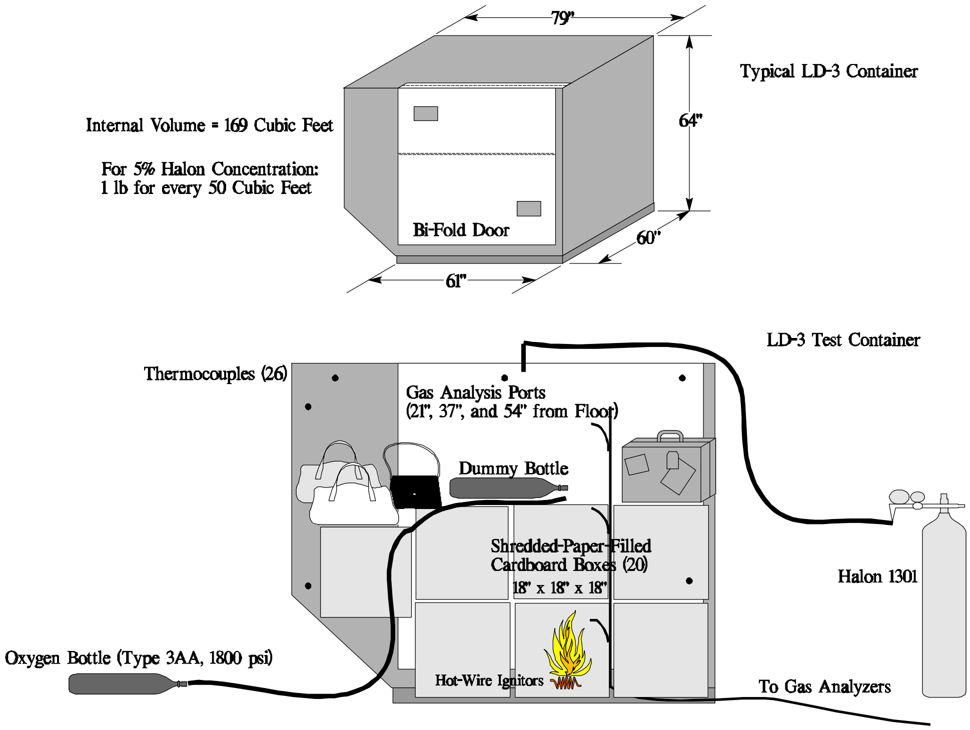

Figure 4. Test Arrangement in LD-3 Container

<u>Test Execution</u>. During all LD-3 tests, the basic configuration and execution remained the same. A nichrome wire igniter was energized in the bottom center "fire box", and a fire was allowed to progress until a significant amount of smoke was produced and the in-box thermocouples indicated the presence of fire. Once this occurred, the halon 1301 was slowly bled into the test container until at least 3% concentration was achieved. Since the first fire test employed an 11 cubic foot oxygen release, the temperature results obtained during the oven test were set as the initial test conditions. A "dummy" cylinder identical to the 11 cubic foot walkaround cylinder was placed in the fire load and outfitted with thermocouples. When the temperatures of the dummy cylinder reached the temperatures achieved during the oven test, the release of oxygen into the container was initiated. The oxygen was supplied by a remote 11 cubic foot cylinder, and transferred through a 0.375 inch diameter copper line approximately 15 feet in length. At the end of the discharge line, a fitting was installed to deflect the oxygen flow in a 360-degree pattern to prevent whipping of the line.

<u>LD-3 Test Results</u>**.** During the first test, several small rag-filled duffel bags and a large suitcase were also placed on top of the shredded-paper-filled boxes. The dummy cylinder was placed amongst this luggage, which was also the area where the gaseous oxygen was discharged. After ignition of the paper filled fire box, the fire was allowed to develop for approximately 18 minutes, at which point the temperature in the fire box had reached 600^{o}F, and a large amount of smoke was emanating from the edges of the container. Halon 1301 was then discharged into the LD-3 container, initially reaching a concentration of 8% at the top station (54 inches from floor).

The 1301 concentration was allowed to decay until 30 minutes into the test, when it had decreased to between 3.5 and 4.0%. At this point, the 11 cubic foot oxygen cylinder was opened, but a problem with the valve prevented a rapid discharge. Instead of emptying in 5 seconds, as evidenced during the oven test, the bottle required approximately 2 minutes to fully discharge. A review of the test data indicated the oxygen concentration inside the container rose from approximately 7% to 16% during the discharge. Slight increases in temperature were observed, but the oxygen release had little overall impact on the fire. The aluminum container ceiling did not allow flames to burnthrough at any time. At 60 minutes, the container was opened and the remaining fire was extinguished. Much of the original fire load was intact, as only 6 of the 20 boxes were burned, and there was no evidence of fire in and around the area of oxygen release.

Several adjustments to the test setup and execution were made prior to the second test. First, it was determined that by switching to an alternate valve port, the contents of the oxygen cylinder could be released in a much shorter duration (5 seconds). Second, the oxygen was released closer to the fire box in order to increase the chance of direct interaction with flaming combustion (figure 5). Third, the LD-3 container was modified to allow for more ventilation, which would provide quicker fire development.

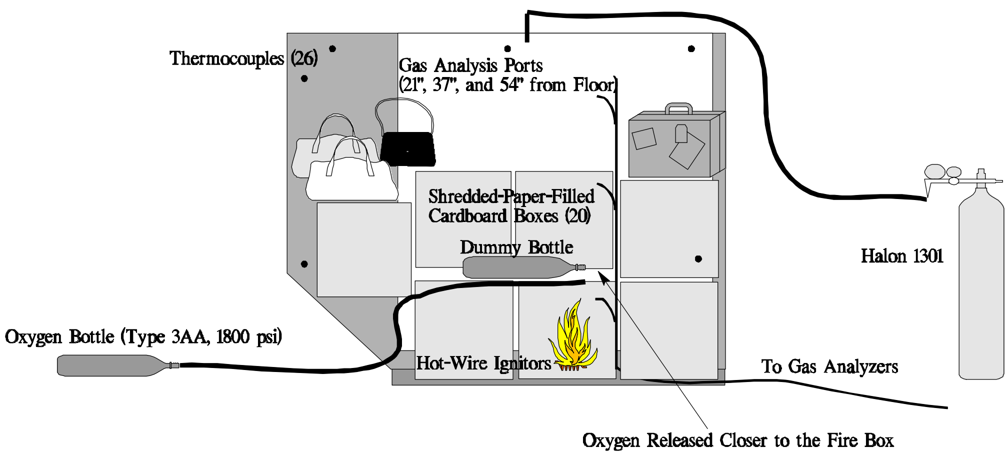

Figure 5. Test 2 and 3 Arrangement in LD-3

During the second test, the fire developed more rapidly, and Halon 1301 was deployed 3 minutes into the test. The concentration of halon reached 10% then slowly tapered off, but the fire was nearly extinguished as the halon concentration was initially too great. In order to continue with the test, a second ignition source was activated inside the box at approximately 14 minutes. The temperatures began to increase, and the oxygen was released at 17 minutes (the halon concentration was approximately 3.8% at the time of oxygen release). Upon release, the smoldering fire erupted violently, as observed via video monitors. Visible flames appeared at one edge of the LD-3 container. Although violent, the eruption was short in duration, and the fire was contained. The fire did not burn through the aluminum ceiling of the container. When the oxygen was released, the concentration was initially 15%, but quickly reached 24%. The test was allowed to progress an additional 23 minutes (40-minute total) without interruption. At this point, the test was terminated, and the container was opened up for extinguishment of any remaining fire. Approximately 50-60% of the fire load (cardboard boxes) was undamaged. Although the test was executed as planned, there was concern over the amount of oxygen released into the fire, as a pre-existing leak in the cylinder valve was discovered just prior to the test. For this reason, the test was repeated in an identical manner.

During the repeat test (test 3), the fire was initiated in an identical fashion, but the halon 1301 was bled into the container more slowly, to simulate an actual situation whereby the container is inside a totally flooded compartment at 3%. After 31 minutes, the temperature inside the fire box was approximately 800^{o}F, and the oxygen concentration inside the container was about 8%. At this point, the oxygen was discharged. The release of oxygen again caused a violent reaction inside the container, which produced enough pressure to force open taped seams on the container in several locations. Although the event produced elevated temperatures inside the fire box (1300^{o}F), it was again very short in duration, much like the previous test. After about 30 seconds, the conditions inside the box resumed to pre-release conditions. In fact, the temperatures appeared to be even lower, indicating that the oxygen release had resulted in an intense combustion period, leaving reduced levels of oxygen and temperature in its wake. Halon was continually bled into the container during the test to maintain 3%, and the test progressed from this point on for another 18 minutes (50-minute total) without incident.

Although the 11 cubic foot oxygen release produced a severe condition inside the container, it was short enough in duration to not overcome the suppression capabilities of the halon 1301. Since the planned test effort was to continue introducing greater oxygen quantities into the container until an uncontrollable fire was produced, twice the amount of oxygen was planned for the fourth test. In an effort to expedite testing, a large oxygen cylinder was acquired from a cutting torch and fitted with a manual on-off 90-degree valve. This allowed subsequent tests to be conducted at various discharge quantities, and alleviated the need to purchase expensive cylinders of various sizes. It was predetermined that 22 cu ft of oxygen weighed 1.8 lb., so the cylinder was placed on a digital scale and the time required to release this amount from the cylinder was measured. This was observed to be 5 seconds. The execution of the test remained identical to the previous three: light the fire in the cardboard boxes, bleed halon 1301 into the container until 3% or greater, then discharge oxygen when the temperatures on the dummy cylinder were 300^{o}F. The only minor deviation was the loading of the cardboard boxes, which

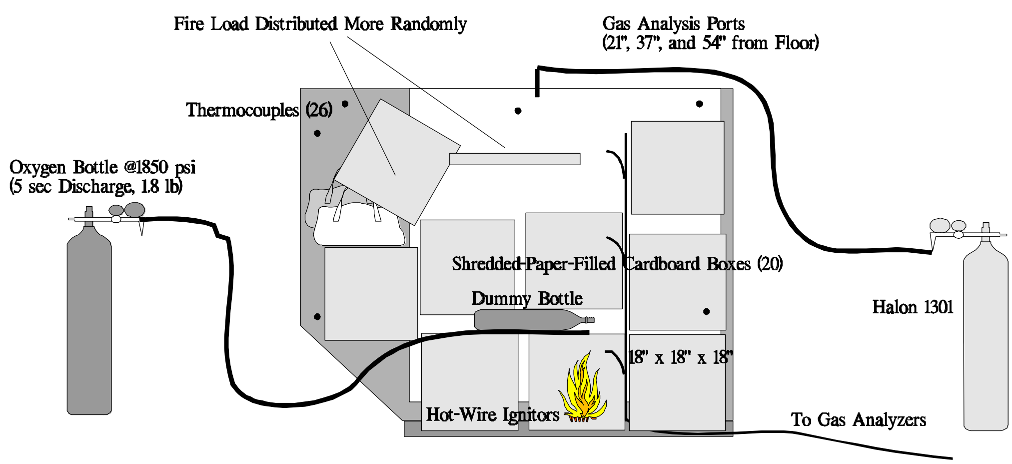

Figure 6. Test 4 Arrangement in LD-3 Container

were placed more randomly to allow for greater air circulation and better fire development (figure 6).

During the fourth test, one of the three dummy cylinder thermocouples had reached a temperature in excess of 300^{o}F at approximately 6 minutes. One of the other two dummy cylinder thermocouples appeared to be malfunctioning, so a determination was made to allow the test to progress a little further, since the remaining thermocouple was still well below 300^{o}F. At 12 minutes 30 seconds into the test, the conditions were right for oxygen release, as the halon concentration was between 3% and 3.2%. Upon release, the front surface of the container was partially blown off, and flames shot out around the periphery in a violent fashion. An attempt was made to maintain the halon concentration at 3% to simulate a container inside a flooded compartment, but all of the gas analysis intake ports were clogged, so there was no way of tracking the concentration. The test was allowed to progress, as flames were beginning to burn through the aluminum ceiling. After 21 minutes, the flames were extinguished, but not before burning completely through the ceiling and part of the front side of the container, totally destroying it. A review of the thermocouple data indicated dramatic increases in temperature in the container four walls and ceiling immediately following the oxygen release.

TESTING OF ATA SPECIFICATION 300, CATEGORY I CASES

Additional tests were conducted in the oven to determine the level of thermal protection offered by a variety of currently available overpacks (cases) meeting ATA specification 300, category I. The overpacks were available in a variety of constructions, all for the purpose of protecting cylinders from impact damage that may occur during shipment. The most common cases are manufactured from plywood laminated with ABS plastic. Other designs include rotationally molded polyethylene, aluminum, fiberglass, and injection molded plastic. The test cases were designed to house the 76.5 cubic foot cylinder (9 inches by 30 inches). Because some of the cases could not be designed properly to provide adequate wall thickness and still remain small enough to fit inside the test oven, the testing was limited to 3 cases supplied by: Bill Thomas Associates (BTA), Viking Packing Specialists, and Anvil. During tests, the cylinder and overpacks were subjected to the same 400^{o}F environment used during tests performed on the unprotected cylinders. Small access holes were drilled into each case and fitted with compression-type bulkhead fittings to allow for the passage of the three thermocouple wires used to monitor the cylinder surface temperature.

<u>Overpack Test Execution</u>. During the first test, the empty 76.5 cubic foot oxygen cylinder was placed inside the Viking overpack, and the three thermocouples were attached to the cylinder surface. The case exterior was constructed of 0.1875-inch thick polyethylene thermoplastic. Two densities of polyethylene foam were glued to the interior side of the case for impact resistance (figure 7).

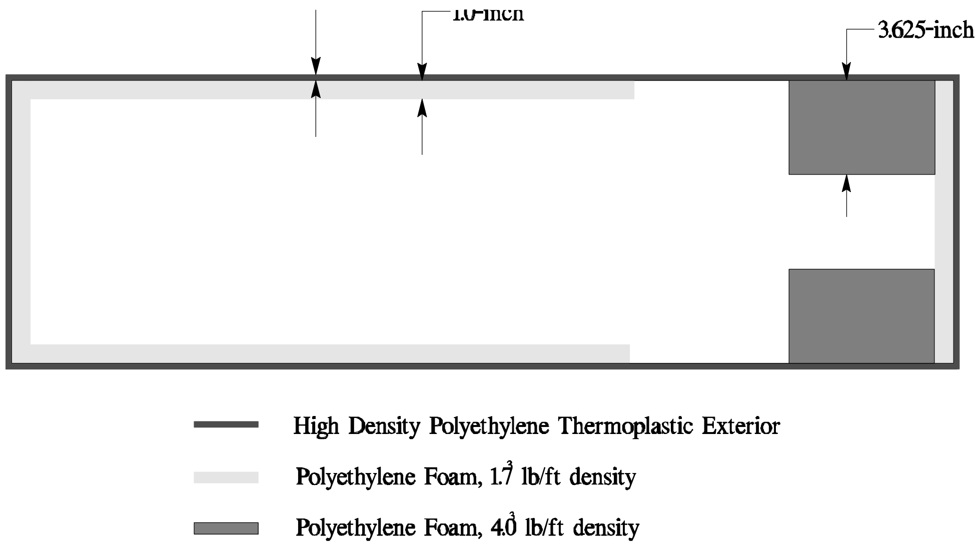

Figure 7. Standard Viking Overpack

After start of the test, the oven temperature quickly rose to 350°F within 10 minutes (figure 8). At approximately 60 minutes, the cylinder surface temperatures remained below the point of rupture disc activation, ranging from 230°F to 280°F. However, significant quantities of smoke

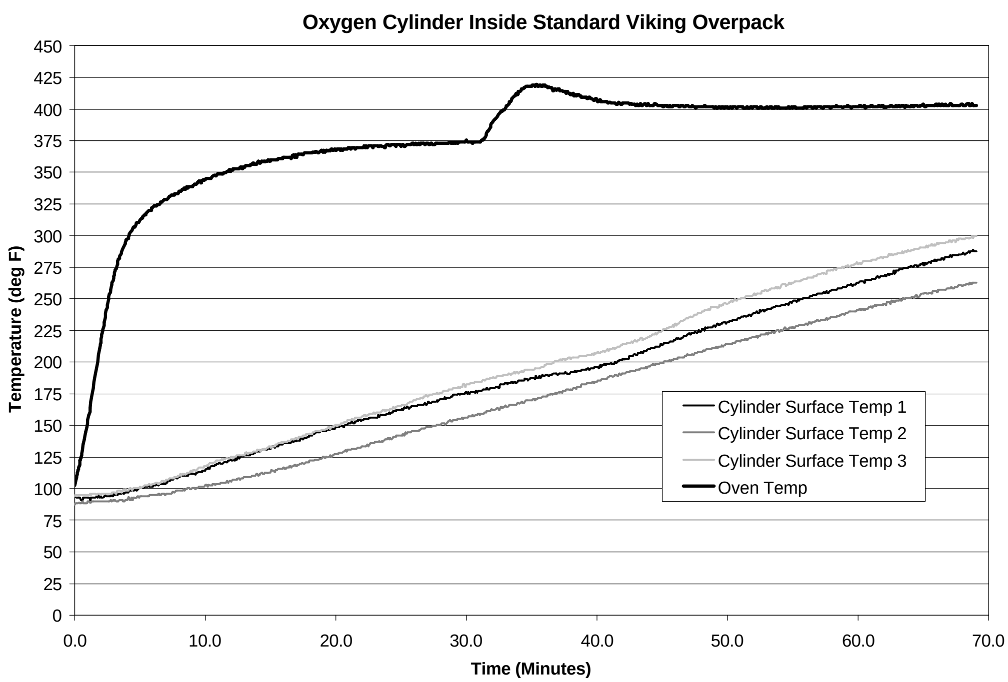

Figure 8. Oven Test Results Using 76.5 ft^3 Cylinder Inside Standard Viking Overpack

began to emerge from the test oven vents. The test was terminated at 69 minutes, with the maximum surface temperature reaching 300°F. Upon opening the test oven door, an examination revealed the entire overpack had melted and formed a plastic coating around the cylinder, with excess material puddled at the floor of the test oven.

Subsequent tests were conducted on ATA Specification 300 cases in which the 76.5 cubic foot cylinder was charged with nitrogen, with a line piped from the relief valve through a bulkhead fitting in the case to an oven access hole, allowing pressure venting external to the test oven. An additional line was passed from the valve through a bulkhead fitting to an externally mounted pressure gauge that could be monitored continuously. Due to a problem with the valve system, the cylinder could only be charged to 1500 psi, and not the full 1800 psi normally achieved.

During the second test, the charged cylinder was loaded into the overpack supplied by Bill Thomas Associates (manufactured by A&J Manufacturing Company). This case was constructed of plywood laminated with fiberglass matting impregnated with epoxy resin. On the interior of the case, urethane-type foam was glued to the inner sidewalls to provide the required impact protection. A plywood brace was also mounted near one end to support the neck of the cylinder, and a 2-inch thick layer of polyethylene foam was glued to the other end (figure 9).

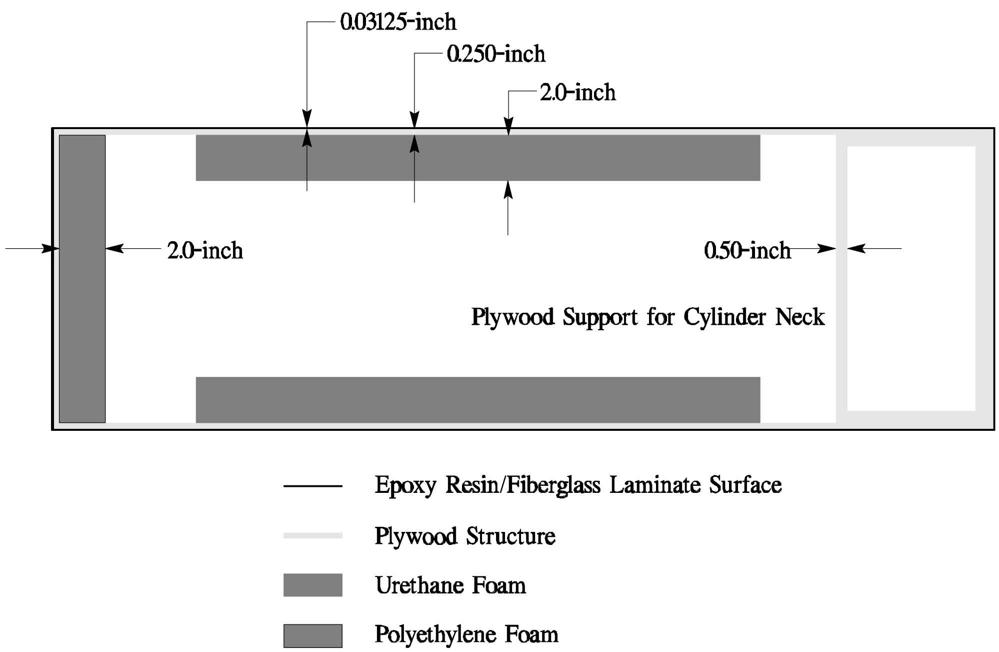

Figure 9. Schematic of Bill Thomas Associates Overpack Construction

After placing the cylinder/overpack on several bricks inside the test oven, the unit was ramped to 400°F (figure 10). After 60 minutes, the cylinder surface temperature had reached 300°F, the temperature at which the relief disc typically fails (due to the slightly lower pressure inside the bottle at the start of the test, the pressure was below the level needed to activate the burst disc at this temperature). The test was terminated, and an inspection of the overpack was made. The inspection revealed slight delamination of the fiberglass exterior surface, as the heat began to break down the epoxy resin. The interior of the overpack revealed no damage to the urethane foam, however the polyethylene foam used in the end had completely melted.

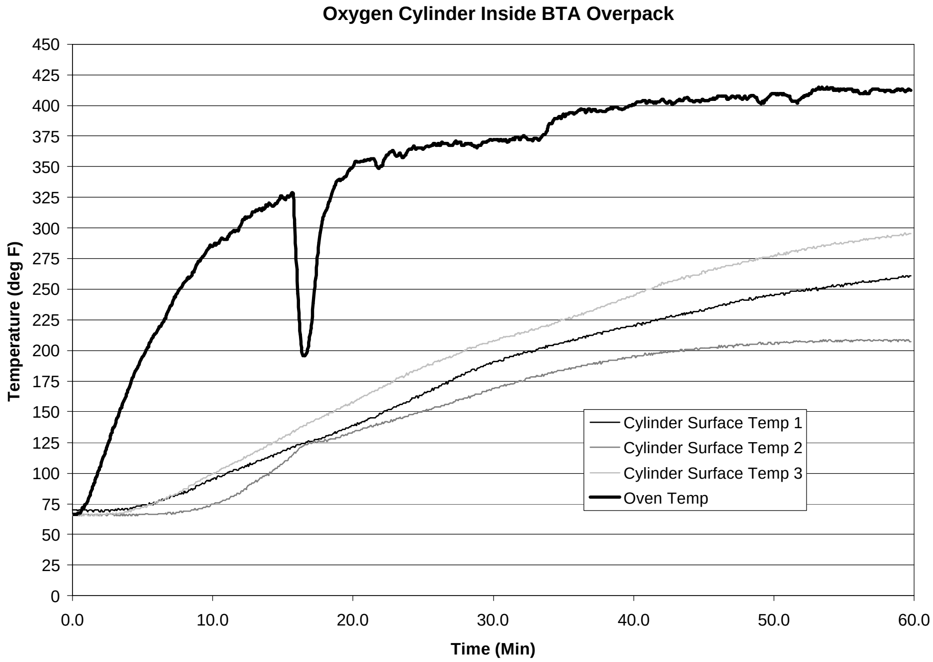

Figure 10. Oven Test Results Using 76.5 ft^3 Cylinder Inside BTA Overpack

During the next test, the charged cylinder was loaded into the Anvil case. This case resembled the BTA case, in that it utilized plywood construction faced with a thermoplastic (figure 11). Urethane foam was glued to the interior side of the plywood, approximately 1 inch thick. Upon

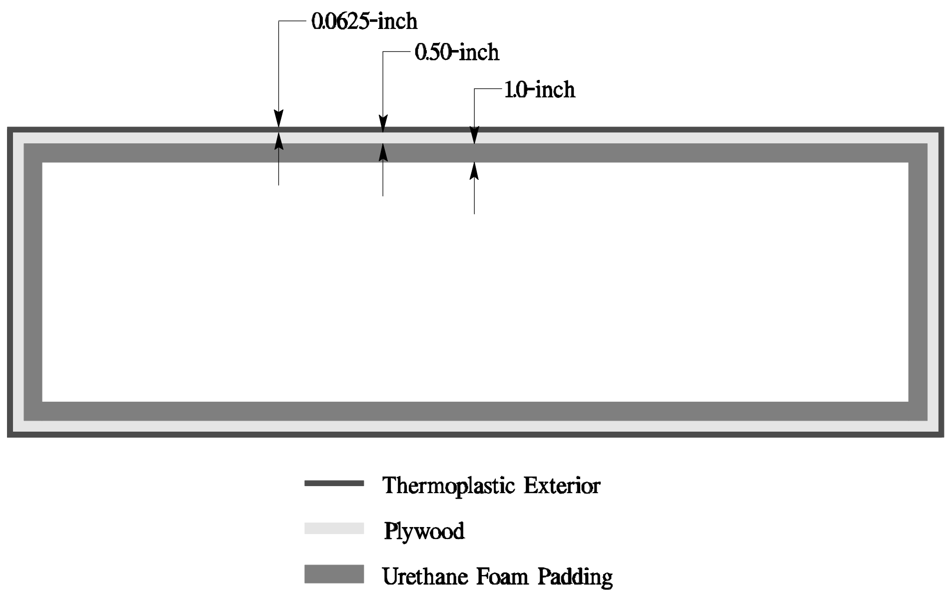

Figure 11. Schematic of Anvil Overpack Construction

test initiation, the oven temperature approached 400°F in approximately 15 minutes (figure 12).

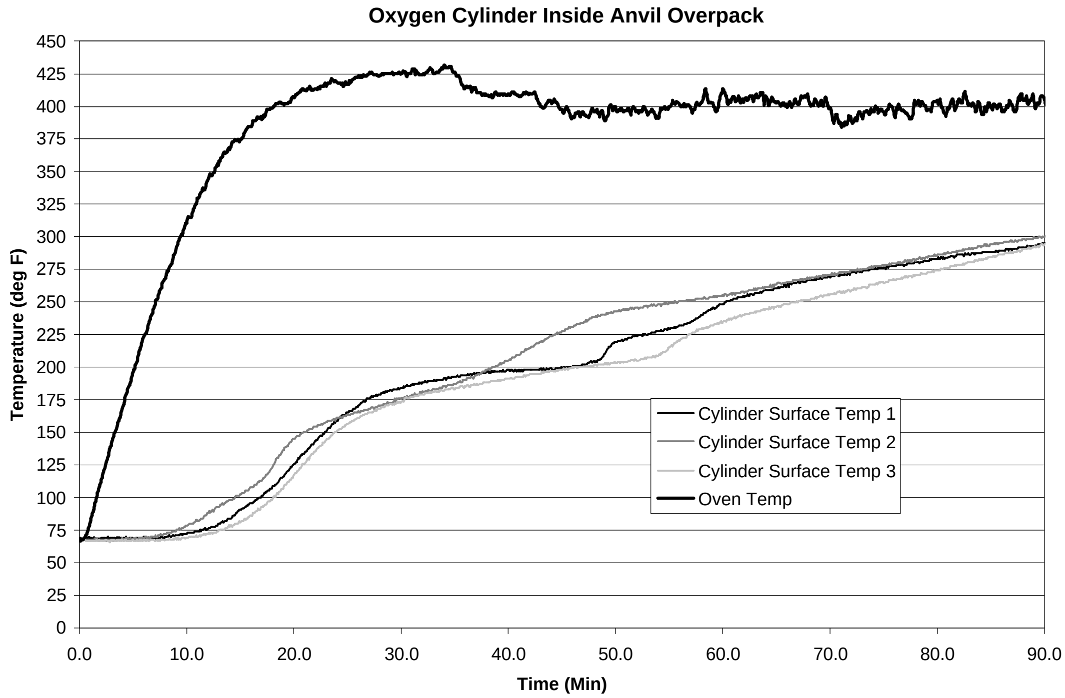

Figure 12. Oven Test Results Using Anvil Overpack

During the test, the temperature of the cylinder surface reached a maximum of 300°F at 90 minutes, at which point the test was terminated. A post-test inspection revealed melting of the exterior thermoplastic surface, exposing the plywood structure in several areas. In addition, the glue used to adhere the urethane foam to the plywood interior surface had melted into a black oily substance, allowing the foam to become displaced in several areas, especially the upper surface.

In an effort to evaluate the potential increase in thermal protection offered by a modified system, additional tests were performed on overpacks specifically designed for this purpose. The cases were manufactured by Viking, and contained an array of materials aimed at insulating a cylinder placed inside. During the first test, the empty 76.5 cubic foot oxygen cylinder was placed in the overpack, which was situated on several stacked bricks inside the oven. A bulkhead compression fitting mounted to the case allowed for the passage of thermocouple wires for the purpose of measuring the cylinder surface temperature. The overpack exterior consisted of a heat resistant thermoplastic known as Kydex. A 1-inch thick fiberglass batt material was sandwiched between the exterior layer of Kydex and an additional layer of Kydex of the same thickness (figure 13). A layer of polyethylene foam was glued to the internal layer of Kydex to provide impact resistance. After test initiation, the oven temperature reached 400°F in 10 minutes. The test was allowed to progress for approximately 60 minutes, at which point large quantities of smoke began to appear from the test oven vents. The temperature of the cylinder surface never exceeded 100°F during the test (figure 14). A post-test inspection revealed the source of the smoke was from the two ends of the case, which had come in contact with the oven heating elements. After heating the case, the thermoplastic lost some of its structural integrity, allowing the ends to sag and eventually come in contact with the oven surface. In addition, the latch mounts had pulled away from the case due to the rivets pulling through the heat-softened thermoplastic exterior, exposing the fiberglass insulation. The interior of the case was undamaged.

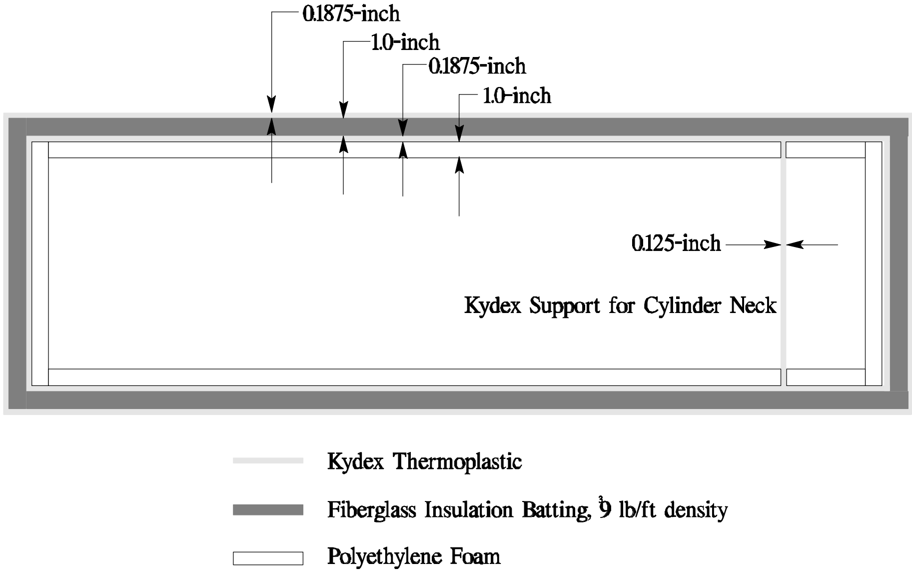

Figure 13. Schematic of Modified Viking Overpack Using Fiberglass Insulation

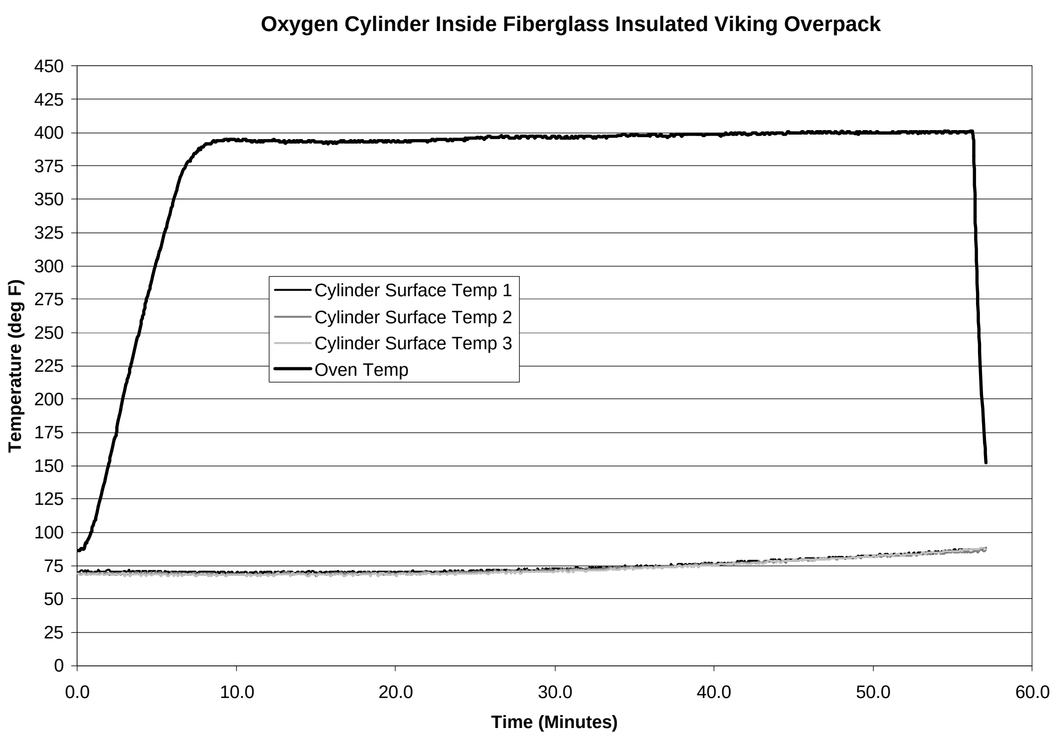

Figure 14. Oven Test Results Using Modified Viking Overpack with Fiberglass Insulation.

A subsequent test was performed on an upgraded version of the thermally protected case. The new design utilized an aluminum faced rigid insulating foam in place of the fiberglass batting (figure 15). External and internal layers of Kydex surrounded the rigid foam. After loading the charged cylinder into the new design case, the oven was activated and the temperature approached 400°F in approximately 15 minutes. During the test, the temperature of the cylinder surface reached a maximum of 210°F at 90 minutes, at which point the test was terminated. A post-test inspection revealed the external layer of Kydex had melted and burned in several locations, exposing the aluminum foil face of the rigid foam insulation panel, which had remained intact. The inner layer of Kydex was slightly warped, but had not changed color. However, the cylinder and valve assembly had become severely discolored as a result of combustion of the Kydex and possibly the rigid foam panel. Due to a malfunction with the data acquisition, the temperature versus time plot obtained during the test was unable to be retrieved.

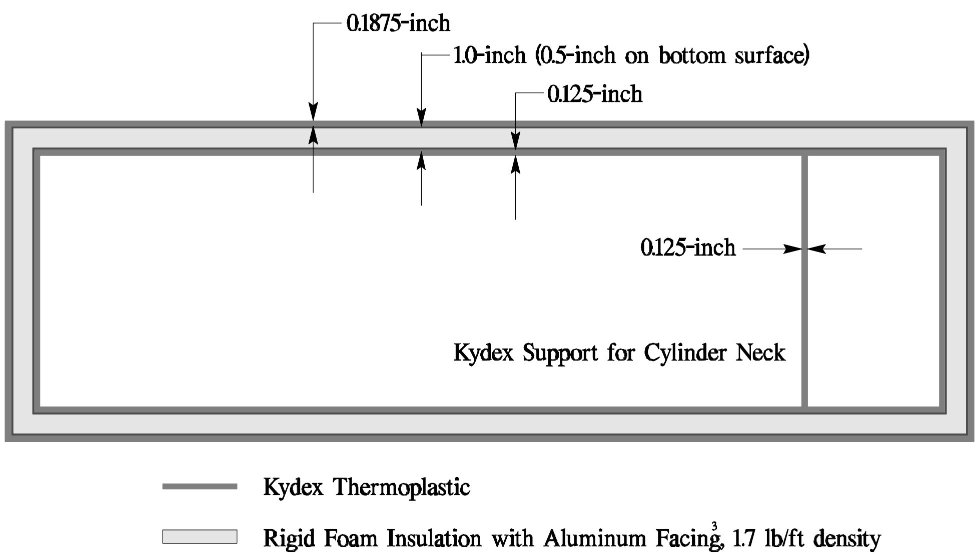

Figure 15. Schematic of Modified Viking Overpack Using Rigid Foam Insulation

CONCLUSIONS

Although the 11 cubic foot oxygen release into the test container produced a severe event during tests 2 and 3, it was short enough in duration to be contained. The fire load of cardboard boxes may have been too tight to allow for fire development, as actual baggage is typically loaded more randomly, allowing greater air circulation. The results of test 4 more clearly indicate the potential of severity during an oxygen-enriched fire. During this test, the front surface of the container was partially forced open from the heat generated during the release of 22 cubic foot of oxygen. Larger amounts of oxygen could create even more violent results. It is possible that the resultant forces generated from the expanding hot gases generated during oxygen introduction could dislodge the cargo liner, allowing the fire suppression agent to escape, causing a loss in fire fighting capability.

The oxygen quantities used in these four tests are relatively small in comparison to the amounts available in commonly used cylinders. As shown in the initial oven tests, a fairly insignificant amount of heat (300^{o}F) can cause the cylinder rupture disc to activate, initiating a full discharge of oxygen in a short duration. Further tests conducted on currently available overpacks have shown that a significant delay in the activation of cylinder relief discs is possible. During tests, two overpack designs provided between 60 and 90 minutes of protection. An overpack designed specifically for thermal protection was capable of maintaining very low cylinder temperatures (less than 100^{o}F) for 60 minutes, suggesting extended periods of cylinder protection are achievable. It is recommended that a suitable standard representative of actual conditions be developed for the overpack materials used for protection of gaseous oxygen cylinders. The standard should reflect extended periods of elevated temperatures typical of a suppressed class C compartment fire. In addition, the overpack materials should also be capable of withstanding open flames for short duration. This condition could occur immediately after fire development, just prior to activation of the suppression system and subsequent agent dispersal.